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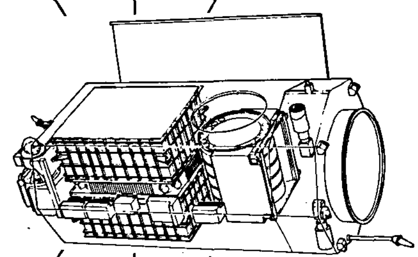

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ELEMENTAL ABUNDANCES OF ULTRAHEAVY COSMIC RAYS

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ELEMENTAL ABUNDANCES OF ULTRAHEAVY COSMIC RAYS

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ABSTRACT

The elemental composition of the cosmic-ray source is different from that which has been generally taken as the composition of the solar system. No general enrichment of products of either r-process or s-process nucleosynthesis accounts for the differences over the entire range of ultraheavy (Z>30) elements; specific determination of nucleosynthetic contributions to the differences depends upon an understanding of the nature of any acceleration fractionation. Comparison between the cosmic-ray source abundances and the abundances of C1 and C2 chondritic meteorites suggests the possibility that differences between the cosmic-ray source and the "standard (C1) solar system" may not be due to acceleration fractionation of the cosmic rays, but may be due instead to a fractionation of the C1 abundances with respect to the interstellar abundances.

INTRODUCTION

The composition of ultraheavy (UH) cosmic rays (those with atomic number, Z, greater than 30) has significance for the subjects of this symposium in two ways. First, we can look for a composition which carries the signature of a particular process of nucleosynthesis, or which

reflects a different mixture of processes than is seen in the composition of the solar system. In particular we look for abundance peaks characteristic of either r-process or s-process nucleosynthesis. Second, we can seek the signature of some atomic process that may reflect the conditions under which the cosmic-ray acceleration takes place. In particular, we examine the correlation between deduced elemental abundances at the cosmic-ray source and the first-ionization potential of the elements, a correlation which was first noticed in lighter elements.

In both cases the approach is to compare the observed cosmic-ray abundances with those which would be expected from a cosmic-ray source of some standard composition. Differences between the cosmic rays and the standard are examined for evidence of one of the signatures described above. This comparison requires a propagation calculation which takes account of fragmentation of cosmic-ray nuclei due to nuclear interactions in the interstellar medium /1,2/. In this paper we confine the discussion to the elements which are relatively abundant compared with heavier elements, so that the conclusions are relatively insensitive to the details of the propagation model.

The primary standard of comparison is usually labeled the "solar system composition" or the "local galactic composition". In this paper we will refer to it as the "standard solar system". Recent compilations of this standard have been made by Cameron /3/, J.P. Meyer /4/, and Anders and Ebihara /5/, all of them based as far as possible on abundances measured in C1 chondritic meteorites. For atomic numbers above 32 or 36, these "solar system" abundances have been decomposed into s-process and r-

process components by Cameron /6/ and by Fixsen /7/, and the cosmic-ray abundances can also be compared with these s-process and r-process compositions.

In this paper we concern ourselves principally with the cosmic-ray abundance measurements made by the Heavy Nuclei Experiment on the third High Energy Astronomy Observatory (HEAO-3) /8/. This experiment has produced charge spectra in which peaks due to the more abundant individual elements are clearly discernible /9,10/; it is the only experiment designed to measure UH cosmic rays which has achieved adequate resolution to resolve such peaks. The cosmic-ray experiment on Ariel-6 /11,12/ recorded comparable numbers of UH cosmic rays, and the general trend of abundances observed by Ariel is similar to that observed by HEAO, but the Ariel results do not display individual element abundances. Because the Ariel instrument has thinner, more uniform walls than the HEAO instrument, Ariel may be expected to provide more reliable measurements of the relative abundances of broad groups of elements of widely separated atomic number, such as the abundance of elements of Z>70 relative to $_{26}$Fe. But without resolving individual elements, such as $_{54}$Xe from $_{56}$Ba, it is not possible to discriminate among an r-process, an s-process, or a "solar-system" composition, nor is it possible to study the effect of atomic properties such as first-ionization potential.

We find that the cosmic-ray source has a different composition from the "standard solar system". However, no general enrichment of products of either r-process or s-process accounts for the differences over the entire range of atomic numbers. The observations in some parts of the charge spectrum suggest either s-process or r-process enhancements, but

conclusions about the nucleosynthesis depend upon uncertain assumptions concerning possible fractionation due to atomic processes associated with the acceleration.

These UH abundances demonstrate a superficial agreement with evidence from lower atomic numbers for a deviation from the "standard solar system" which is correlated with the first-ionization potential. But closer examination shows at least one clear contradiction ($_{32}$Ge) to this correlation. We suggest that rather than looking to exotic processes in the cosmic rays to explain differences from the "standard solar system", we might find the explanation in assumptions that went into establishment of that standard. In particular, we note that elements for which the cosmic-ray source differs from the "standard solar system" are generally those elements for which the abundances found in the solar system differ between C1 and C2 chondrites. Indeed the cosmic-ray source abundances are in closer agreement with C2 abundances /13/ than with the "standard solar system" which is based on C1 abundances.

In the following sections we examine in turn the data in each of the three charge intervals for which inferences about the cosmic-ray source are not strongly dependent upon the propagation model: (1) atomic numbers 32 through 42, (2) 50 through 58, (3) greater than 74. In the first two of these intervals, the HEAO experiment resolved individual peaks at elements of even atomic number. For the rarer nuclei of higher atomic number, peaks at individual elements were not resolved, but limits could be placed on the abundance of $_{82}$Pb relative to the "Pt group" of atomic numbers 76 to 78, and on the abundance of the actinides (Z>88) relative to the "Pt-Pb group". Then, in the final two sections we dis-

cuss the implications of our observations for nucleosynthesis and for differences between the elemental composition of the cosmic-ray source and the solar system.

ATOMIC NUMBERS 32 THROUGH 42

Figure 1 shows a histogram of charge assignments for a subset of our data, selected for high resolution. This data set includes cosmic rays with energy between 0.4 and 1 GeV/amu and cosmic rays which were incident from directions where the geomagnetic cutoff was greater than 8 GV. The low-energy and the high-rigidity parts of this data set do not show significant differences in composition, so they have been combined here. Peaks are evident in these data at elements $_{32}$Ge, $_{34}$Se, and $_{38}$Sr; and a less obvious bump appears at $_{36}$Kr.

We have derived individual element abundances by applying a maximum-likelihood fit to the data, assuming a gaussian resolution function. We are very confident of the resulting abundances for the even-Z elements, particularly those for which peaks are seen in the histogram. For the odd-Z elements the resulting abundances depend critically on the assumed shape of the resolution function, and we can be confident only of upper limits to these abundances. Independent of the fitting, two qualitative points should be evident from the histogram. First there is a clear peak at $_{38}$Sr, of comparable abundance to the peak at $_{34}$Se; and second, $_{37}$Rb is distinctly less abundant than $_{38}$Sr.

The data points in figure 2 /14/ give the abundances of these elements relative to that of $_{26}$Fe. For the odd-Z elements we present 84% confidence upper limits (corresponding to the tops of one-sigma error bars).

For comparison the solid-line in panel (a) indicates the abundances expected at earth for a cosmic-ray source with "standard solar system" /3/ abundances; and the dashed line, for the "standard solar system" modified by an assumed fractionation depending exponentially upon the first-ionization potential. Although there is a general similarity between the cosmic-ray source and the "standard solar system", there are systematic differences of a factor of two or less which we discuss later.

Panel (b) of figure 2 shows the same data, but compared with the s-process component /6/ of the "standard solar system", either with (dashed) or without (solid) the same assumed first-ionization fractionation. In this atomic-number interval the "standard solar system" is principally composed of s-process material, so the agreement between the data and the s-process is about as good as between the data and the "standard solar system".

Panel (c) again shows the same data, but this time compared with abundances expected from a source composed only of the r-process /6/ part of the "standard solar system". This part is not sufficiently abundant to account for the observed cosmic rays. Even if one permits renormalization of the r-process source relative to Fe, as has been done in panel (d) where the data points are again the same but the histograms of panel (c) have been arbitrarily increased by a factor of five, the abundances of elements in this interval relative to one another do not fit the cosmic-ray observation. In particular, cosmic-ray Sr is comparable in abundance to Se, not down by a factor of 2.5 to 4; and more striking, the cosmic-ray Sr is distinctly more abundant than Rb, while the r-

process contribution to the "standard solar system" has distinctly more Rb than Sr.

Thus for atomic numbers in the interval 32 to 42, the cosmic rays are clearly not dominated by products of r-process nucleosynthesis, but they are much more similar to the "standard solar system". In this interval elemental abundances do not permit distinction between cosmic-ray similarity to the "standard solar system" and similarity to a pure s-process, since the "standard solar system" is mainly s-process. Measurements of the isotopic composition of the cosmic rays would be required to make this distinction.

ATOMIC NUMBERS 50 THROUGH 58

Figure 3 /15,16/ is a selected subset of data displaying peaks at even atomic numbers $_{50}$Sn, $_{52}$Te, $_{54}$Xe, $_{56}$Ba, and $_{58}$Ce. The most abundant of these elements is clearly Ba. The cosmic rays are less abundant in this interval than in the interval discussed above, so data selection could not be made as stringent; as a result the resolution is not as good. The inset, which superposes the data modulo two charge units, demonstrates that the peaks at even charges are real.

The data points in figure 4 give the relative abundances of the five elements of even atomic number inferred from maximum-likelihood fits to the data /15/. The histograms are abundances expected near earth assuming various cosmic-ray source abundances. The assumed sources are the "standard solar system" /5/, and the s-process /17/ and r-process components of the "standard solar system". In addition histograms are shown for cases where each of these three sources has been modified by

an exponential dependence on first-ionization potential. In each panel the histograms have been arbitrarily normalized to unit abundance of $_{52}$Te; and the data have been normalized to minimize the mean square deviation between the data and the prediction.

In this atomic-number interval the r-process and the s-process contributions to the "standard solar system" are comparable; Te and Xe, which are principally produced in the r-process, are about equally abundant with Sn and Ba which are principally produced in the s-process. Thus one might hope here to be able to infer the relative contributions of each of these processes to the cosmic-ray source.

Qualitative examination of the six panels of figure 4 demonstrates about equally good fit to the data by an s-process source <u>without</u> any first-ionization fractionation, and by the "standard solar system" <u>with</u> first-ionization fractionation. In other words, the observed enhancement of Sn and Ba relative to Te and Xe can be explained qualitatively by noting either that Sn and Ba are s-process elements or that these are the elements of lower first-ionization potential.

In a formal sense, one can ask what linear combination of r-process and s-process sources best matches the observed cosmic-ray relative abundances of these five elements. Ignoring first-ionization fractionation, the result /15,16/ is an r-process to s-process ratio which is 0.20 (+0.18/-0.14) times that of the "standard solar system"; in other words, a cosmic-ray source which is mainly s-process. With the particular model of first-ionization fractionation used here, the formal result /15,16/ is an r-process to s-process ratio which is 1.5 (+0.8/-0.5) times that of the "standard solar system"; in other words, consistent

with some r-process enhancement or with the "standard solar system". Thus any conclusion about the nucleosynthesis of these heavy cosmic rays requires an understanding of the nature of the apparent first-ionization fractionation which is evident in comparison of lighter cosmic rays with the "standard solar system".

ATOMIC NUMBERS GREATER THAN 74

At the highest atomic numbers, the abundances are so small that we must be very generous in selecting data if we are to have any reasonable statistics. Figure 5 gives a histogram of assigned charge for events with atomic number fifty and larger /18/. The root-mean-square resolution is roughly one charge unit, so individual elements are not resolved, and the numbers of events in any bin should not be taken as the best estimate of the number of incident cosmic rays of that charge. The data of figure 5 have not been corrected for the effects of fragmentation of the nuclei as they pass through the walls entering the detector. Since these effects are mass dependent, the relative abundances of widely separated charges on this histogram are incorrect. In the following discussion we confine ourselves to the data in the relatively narrow interval above atomic number 74 where these biases are not significant. The data at lower atomic numbers are plotted to demonstrate, by the even-Z peaks between 50 and 58 and by the sharp abundance drops above 56 and above 58, that there is reasonable resolution in this data set.

Of the events with atomic number 74 or greater, 15% are particles with energy less than 1 GeV/amu, for which exposure of a prototype instrument at the LBL Bevalac has given us a direct calibration /19/, and the

deviation of instrument response (principally the response of the ionization counters) from simple Z^2 scaling has been directly determined. The correct charge assignment at $_{79}$Au is ~2.8 charge units lower than that inferred from simple Z^2 scaling when the scale is normalized at $_{26}$Fe, and this calibration has been applied to these low-energy events. The other 85% of the events with Z>73 are particles of higher energy where atomic number is assigned from the Cherenkov signal, and we have assumed simple Z^2 scaling of Cherenkov response, normalized to Fe. Below 1 GeV/amu the Cherenkov response was observed to be close to simple Z^2 scaling, so this is a reasonable assumption; however, calculations of the effect of Cherenkov emission of knockon electrons /20/ suggest that this procedure may overestimate the charges by one or two charge units.

In figure 6 the data points are just the observed numbers of events which were shown in figure 5, with statistical error bars. Unlike the presentations at lower atomic numbers in previous sections of this paper, these data points are raw numbers without any attempt to derive individual element abundances by accounting for instrumental effects. The histograms give the expected observations for various assumed cosmic-ray source abundances; these predictions result from calculations which include interstellar propagation, propagation through the detector, and instrumental resolution, and the calculations have been normalized to the total number of observed events above atomic number 71. In this figure the solar abundances are for the "standard solar system" of Anders and Ebihara /5/, and the s-process and r-process abundances were derived by Fixsen /7/ in the standard way from the "standard solar system". As before, the three lower panels assumed a source fractionation

depending exponentially on first-ionization potential.

The data display a lack of $_{82}$Pb relative to the "Pt-group" ($_{76}$Os, $_{77}$Ir, $_{78}$Pt). This lack of Pb is obviously inconsistent with an s-process cosmic-ray source. Also the data do not appear to agree very well with the "standard solar system". This disagreement would be emphasized if a correction were applied to the charge scale to compensate for a possible overestimate of charges by one or two units. Any kind of correction for first-ionization fractionation which predicts relative enhancement of elements with lower first-ionization potential makes the disagreement between data and prediction greater, because Pb has a relatively low first-ionization potential and so it is enhanced by such a correction. The comparison between the data and these predictions is made more quantitative by the following table which gives the ratio of the expected number of events with atomic number 81 or higher to the expected number with atomic number 74 through 80. The values in this table are to be compared with the observed ratio of 0.26 +/- 0.08.

	Solar System	s-Process	r-Process
no FIP fractionation	0.40	0.67	0.31
with FIP fractionation	0.52	0.78	0.41

Each of these predicted ratios differs from the observation by at least two standard deviations, except for the r-process without any FIP fractionation. It should be noted that the Cameron /6/ decomposition of his /3/ solar system abundances yields an r-process with much less Pb than indicated here. Also Fixsen /7/ has argued that interpolation between r-process isotopes of $_{81}$Tl and $_{83}$Bi strongly suggests a lower r-process abundance of $_{82}$Pb than indicated here. Our observed abundances could be

consistent with those expected from such a "Pb-poor r-process", either with or without FIP fractionation.

Finally, we note that in figure 5 there are 58 events with atomic number greater than 73, but no event with atomic number greater than 86. If we relax the selection requirements as much as possible while retaining reasonable confidence that charges are not widely mis-identified, we find a total of 100 events with atomic number greater than 73 including a single event whose best estimate of atomic number is in the actinide region /21/. This resulting ratio of actinides to "Pt-Pb" of 1% is roughly what would be expected from a "standard solar system" source, but with statistics of one event one cannot exclude a significant enhancement of either r-process or s-process on the basis of this ratio. One can exclude a source composed primarily of freshly synthesized r-process material, in which there was negligible time for decay of short-lived r-process material before the cosmic rays were accelerated.

DISCUSSION -- NUCLEOSYNTHESIS

In the previous three sections, we have presented data in the three intervals of atomic number where the observations permit inferences about the source abundances which do not depend strongly upon the model of interstellar propagation. We have compared the observations with the "standard solar system" and with r-process and s-process components of that standard in an effort to determine whether the cosmic-ray source has a significantly different mix of r-process and s-process material than the solar system. It is clear that the cosmic-ray source composition is somewhat different from the "standard solar system". However, a determination of the nucleosynthetic contributions to these differences

depends upon an understanding of the nature of any acceleration fractionation.

If it is assumed, for example, that there is a first-ionization fractionation, then when compared with the "standard solar system", the cosmic-ray source could be increasingly enhanced in r-process relative to s-process nuclei as the atomic number increases. Thus there is no observed r-process enhancement in the atomic number interval from 32 to 42 where s-process dominates; there is possibly a modest enhancement (factor of 1.5 +0.8/-0.5) from 50 to 58; and there may be mainly r-process nuclei above 74. However, if there is not first-ionization fractionation, then r-process nuclei are dominant only above 74, while s-process nuclei dominate the abundances at lower atomic number.

As indicated by the preceding discussion, it is essential to understand the systematics of any apparent fractionation between cosmic-ray source and "standard solar system" material. In this connection, it also seems appropriate to re-examine the nature of the fractionation which characterizes the different classes of meteorites from which the "standard solar system" abundances are inferred.

DISCUSSION -- COSMIC RAY SOURCE AND SOLAR SYSTEM ABUNDANCES

In figure 7 the ratio of cosmic-ray source (CRS) abundance to "standard solar system" (SS) abundance for various elements is plotted as a function of first-ionization potential (FIP) /22/. All the cosmic-ray data in this figure come from the HEAO-3 spacecraft. For the ultraheavy cosmic rays (Z>30), the data are those discussed above; for the lower atomic numbers the data are from the experiment by the collaboration

between Saclay and the Danish Space Research Institute /23/. (For $_{28}Ni$, $_{30}Zn$, and $_{32}Ge$ the observations by the two experiments are in good agreement.) For data from both experiments the CRS/SS ratios are normalized to unity at Fe. The error bars plotted include the uncertainties in the solar-system abundances assigned by Anders and Ebihara /5/. For the ultraheavy elements the errors include an estimate of the uncertainty due to the propagation model /2/; this is the principal contribution to the error bars for Sn and Te, which have significant secondary components at earth due to fragmentation of Xe and Ba.

Both the ultraheavy cosmic rays and those of lower atomic number seem broadly to show the previously noted /24/ correlation between CRS/SS and first ionization potential. A straight line can be drawn which does not miss many of the data points, suggesting the exponential dependence that has been used in previous calculations. An equally good fit can be obtained with a step function whose value is about unity for FIP less than 8.5 eV and about 0.4 for higher values of FIP /25/. However, the difference between the CRS/SS ratio of Ge and Fe cannot be explained by any model of FIP dependence because these two elements have nearly identical values of FIP.

We note that Ge, like most of the elements of higher FIP, has abundances relative to Fe or Si in C2 chondrites which are about a factor of two lower than in C1 chondrites /13/. The usually accepted explanation of this difference is that the elements which are less abundant in C2 chondrites are the ones which make volatile compounds and the C2 chondrites are thought to be depleted in these volatiles /3,4,5/. An alternative explanation has been suggested /26/, that the C1 chondrites are enriched

in these elements due to effects of solubility in water. Comparisons between solar photospheric observations and either C1 or C2 abundances have been taken to suggest better agreement with C1, but the correlation is not compelling /4,13/.

The part of figure 7 which is reasonably well fit by a value of unity for CRS/SS covers those elements for which C1 and C2 abundances are nearly the same. The deviations from unity are principally for elements where the abundances differ between the classes of chondrites /27/ and for the rare gases whose "solar system" abundance cannot be determined from any of these chondrites.

The points in figure 8 are the same as those in figure 7, except that for those elements where the C1 and C2 abundances differ the ordinate has been multiplied by the C1/C2 ratio; thus the C2 abundances have been substituted for the C1 abundances in the "standard solar system". (For the rare gases, Ar, Kr, and Xe, where the "standard solar system" was based on interpolation, a similar interpolation has been made here between C2 abundances.)

In figure 8, Ge does not appear to be underabundant, nor do Zn and Se; thus the ratio CRS/SS appears to be independent of FIP at least up to 10 eV; and the deviations from unity of the remaining elements are less than before. We have not included in figures 7 and 8 data for elements of atomic number greater than 74 because we have not resolved individual element abundances there. But we note that Pb is one of the elements for which C2 abundances are lower than C1 abundances by about a factor of two; while Os, Ir, and Pt are elements for which C1 and C2 abundances are nearly identical /13/. Thus the discrepancy between the observed

"Pb/Pt" ratio and that expected from a source with the "standard solar system" composition would change to good agreement if the "standard (C1) solar system" were replaced with C2 abundances.

We are not suggesting that we have demonstrated that the proper standard for solar system abundances is precisely C2 chondrites; nor are we suggesting that the cosmic-ray source differs from the solar system by the same assumed depletion of volatiles as appears in C2 chondrites. However, the fact that the cosmic-ray source abundances do not differ significantly from those of the "standard solar system" for those elements whose abundances do not vary among the classes of chondrites, suggests that the cosmic-ray composition may indeed be quite similar to the true composition of the solar system. Furthermore, the similarity of the cosmic-ray source to C2 abundances for the volatile elements suggests the possibility that differences between the cosmic-ray source and the "standard solar system" may not be due to acceleration fractionation of the cosmic rays, but rather it may be due to a fractionation of the "standard (C1) solar system" with respect to interstellar abundances of which the cosmic rays may be reasonably representative. This further suggests the possibility that the true solar system abundances of volatile elements may be uncertain to at least a factor of two, and that the assumption that the C1 abundances are most representative of the solar nebula deserves re-examination.

ACKNOWLEDGEMENTS

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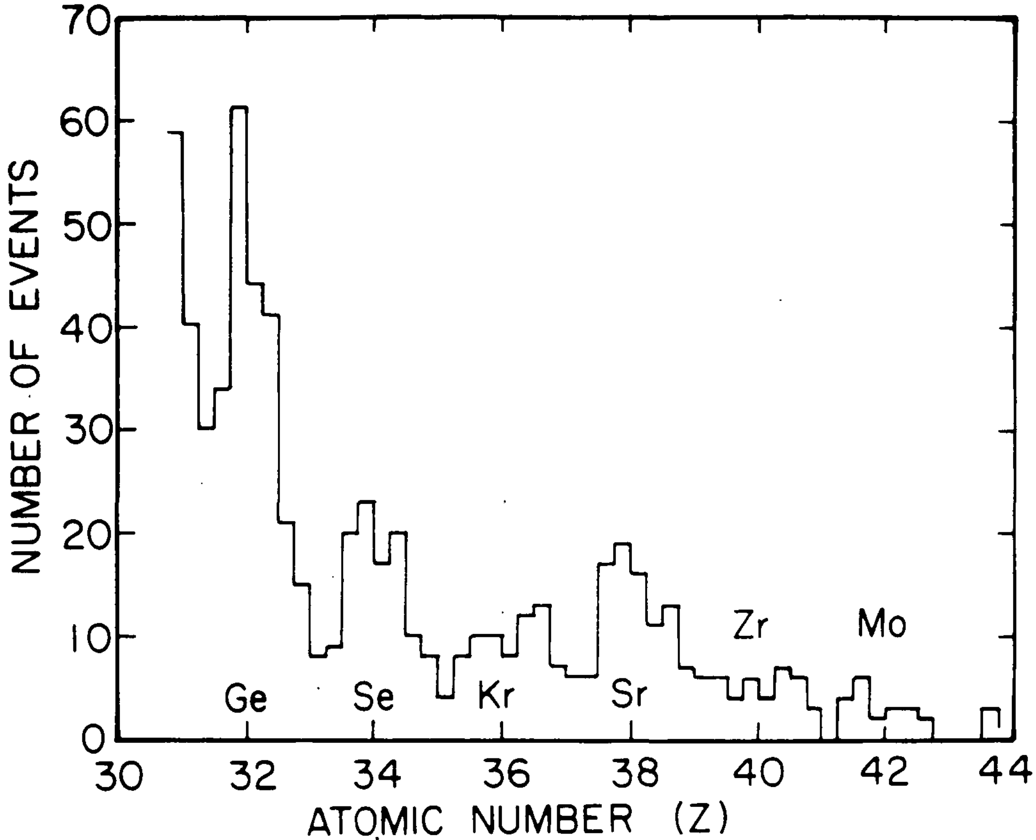

Figure 1. Histogram of charge (atomic number) assignments for cosmic rays with energy between 0.4 and 1 GeV/amu and cosmic rays incident from directions with geomagnetic cutoff greater than 8 GV.

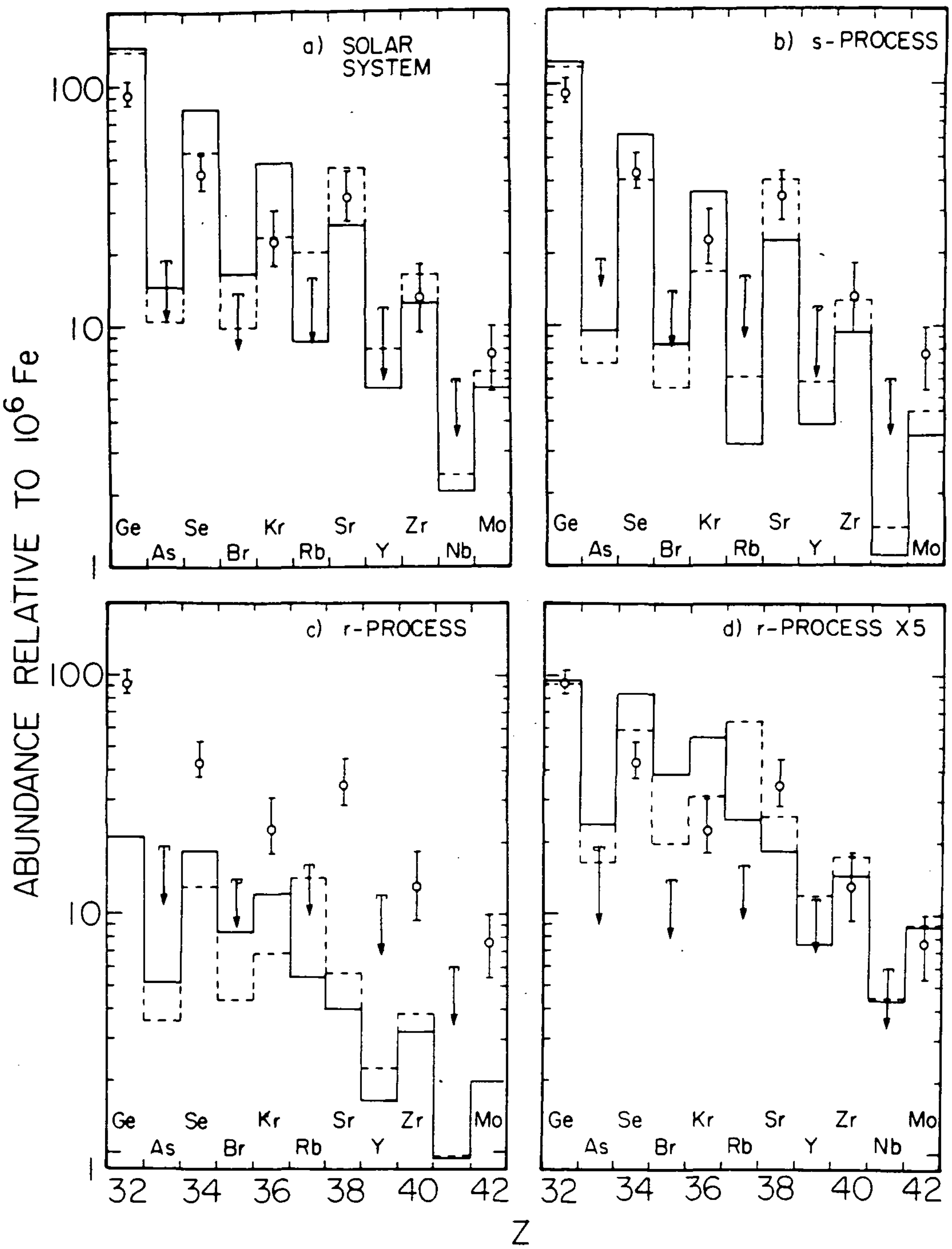

Figure 2. Comparison of measured abundances (data points) with abundances expected from various assumed sources. Solid line histograms assume no first-ionization fractionation. Dashed line histograms assume fractionation which depends exponentially on first-ionization potential.

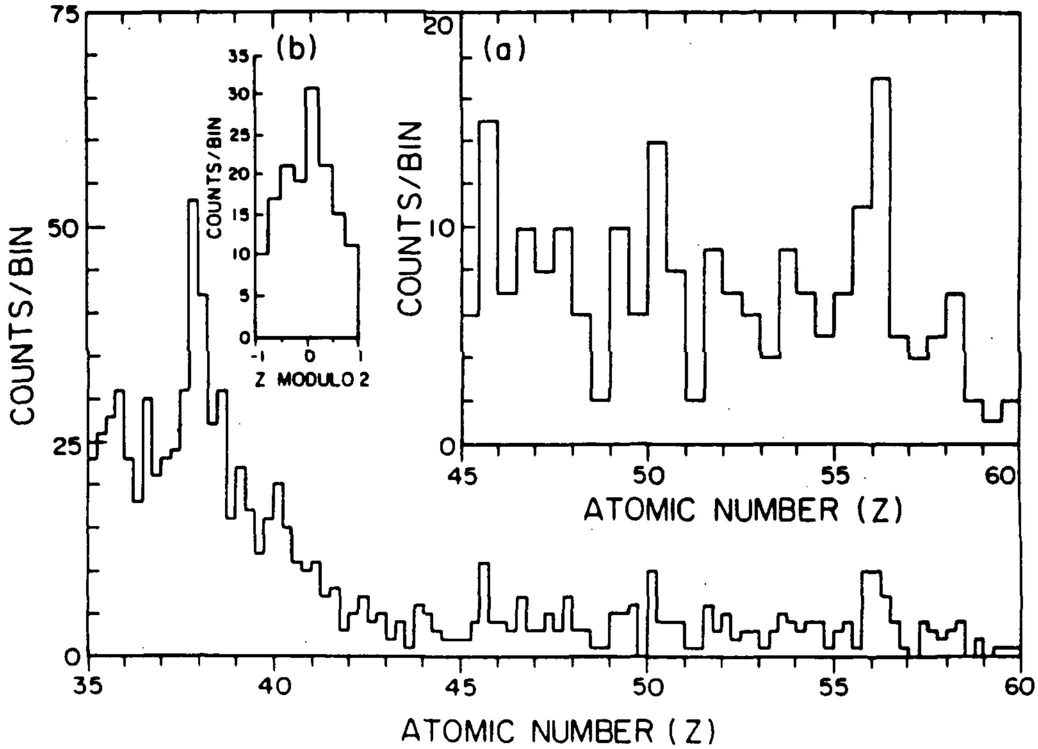

Figure 3. Histogram of charge (atomic number) assignments. Inset (a) expands the Sn - Ce region. Inset (b) is a modulo 2 superposition of events in that region.

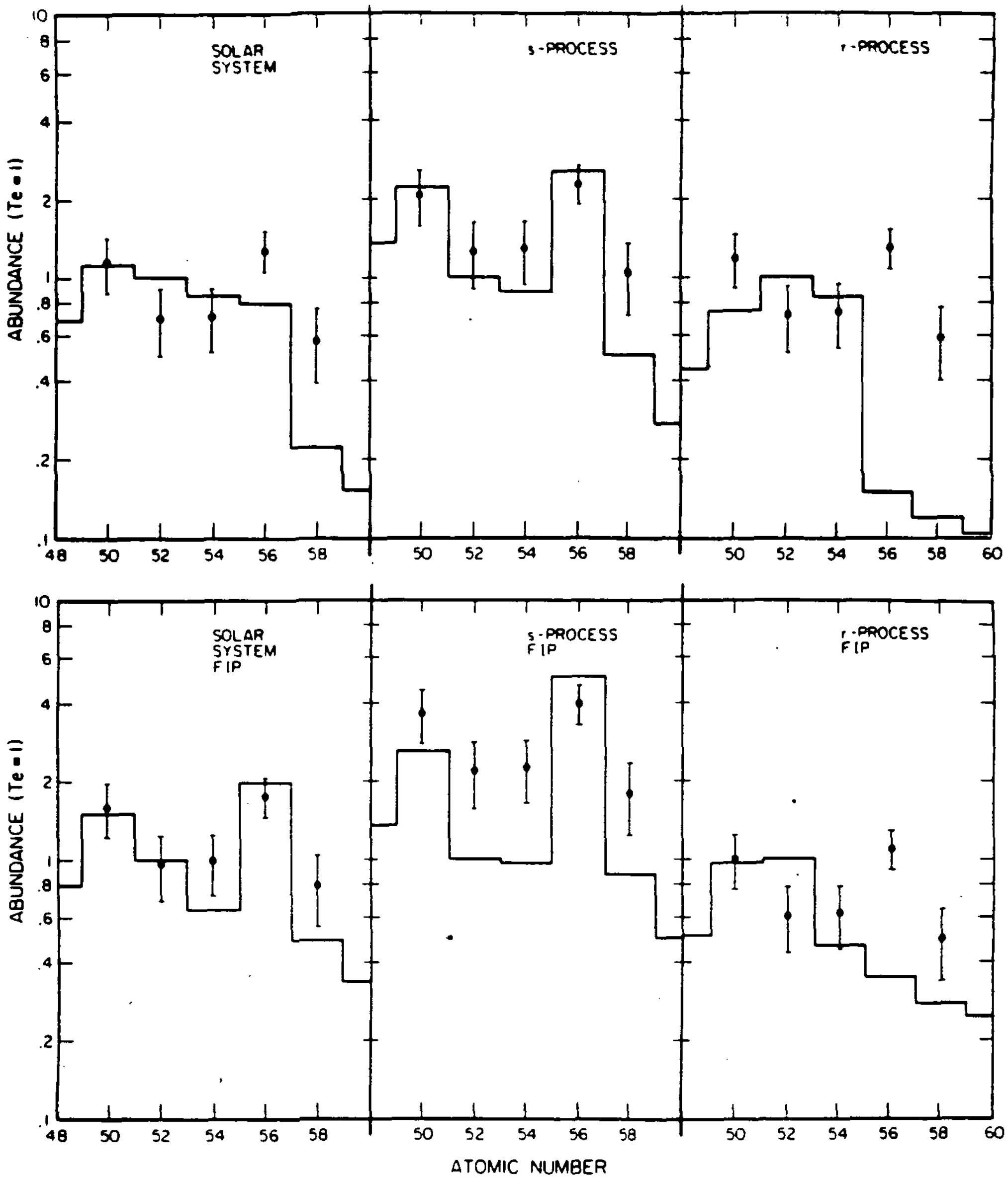

Figure 4. Comparison of measured abundances (data points) with abundances expected from various assumed sources; panels labeled FIP assume exponential first-ionization fractionation.

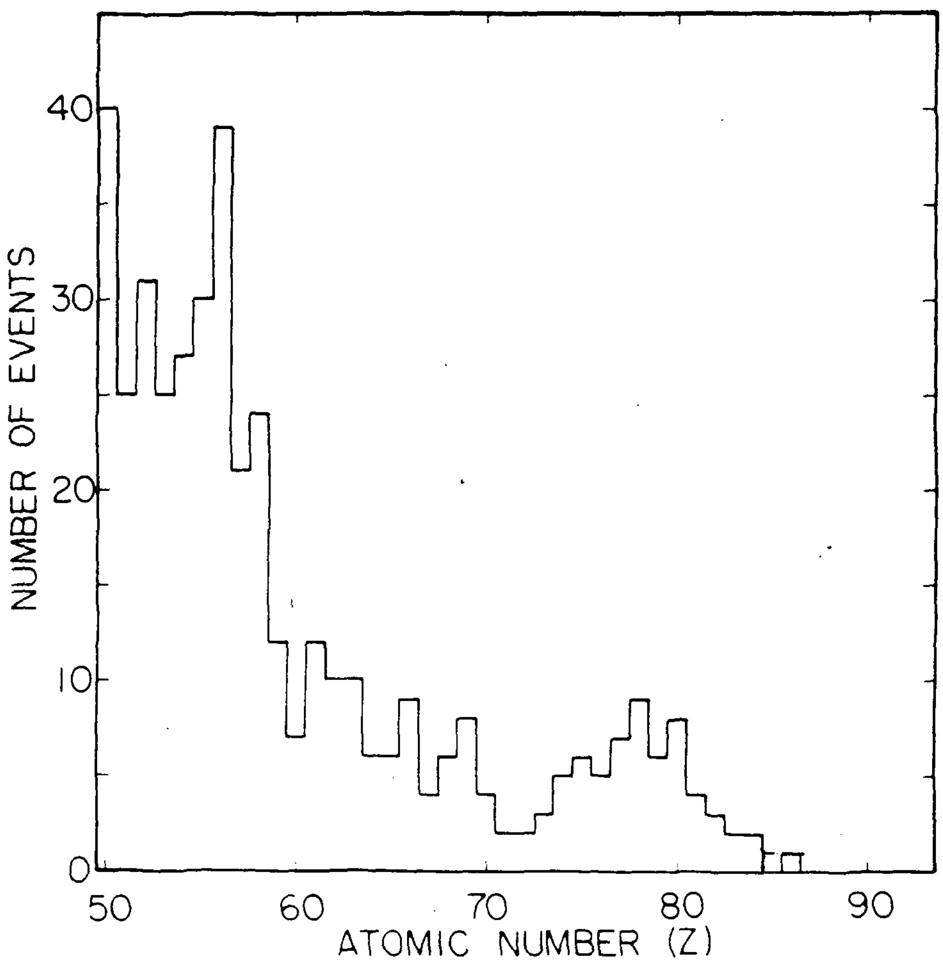

Figure 5. Histogram of charge (atomic number) assignments.

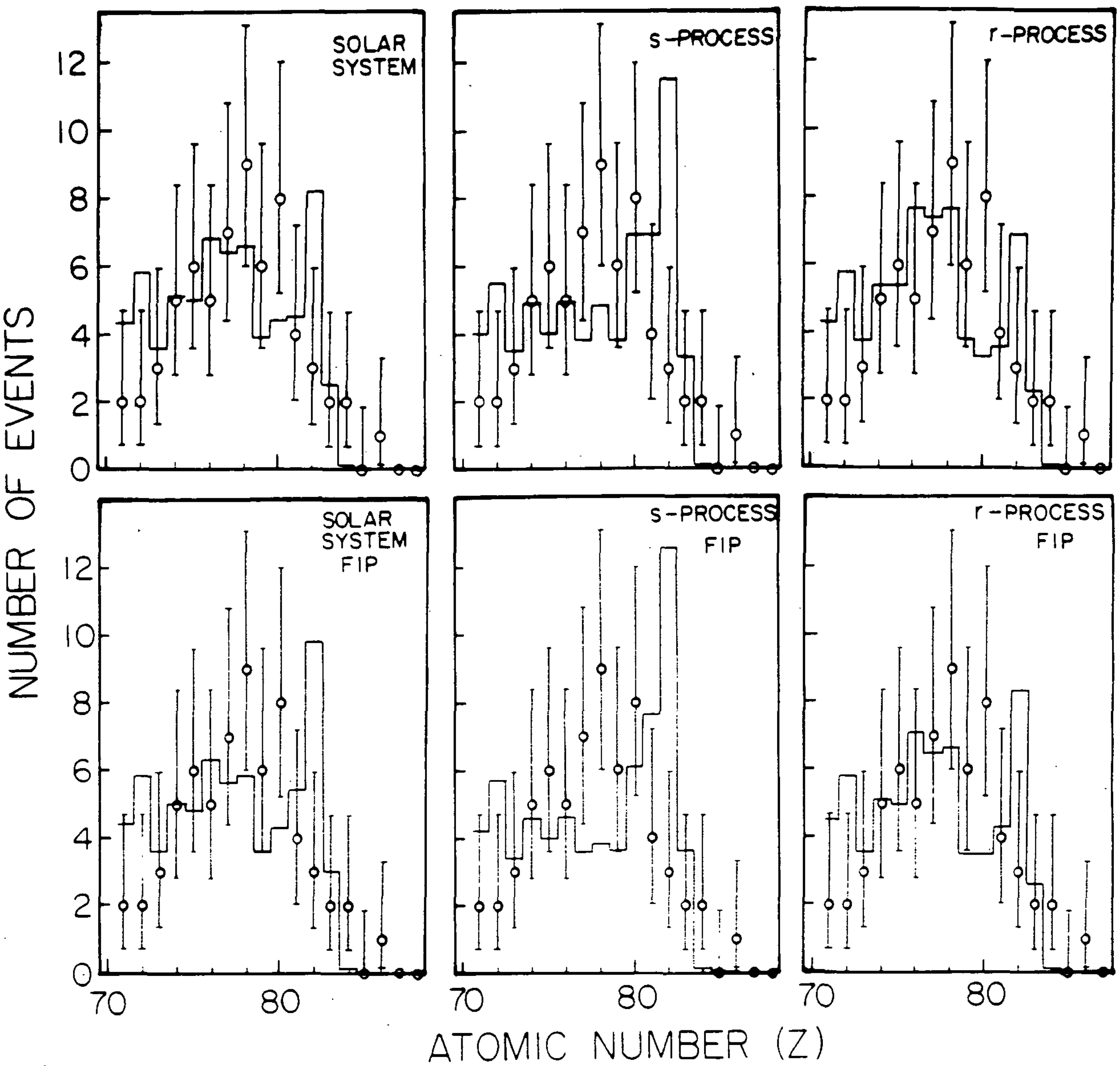

Figure 6. Comparison of observations (data points taken directly from histogram of figure 5) with those expected from various assumed sources; panels labeled FIP assume exponential first-ionization fractionation.

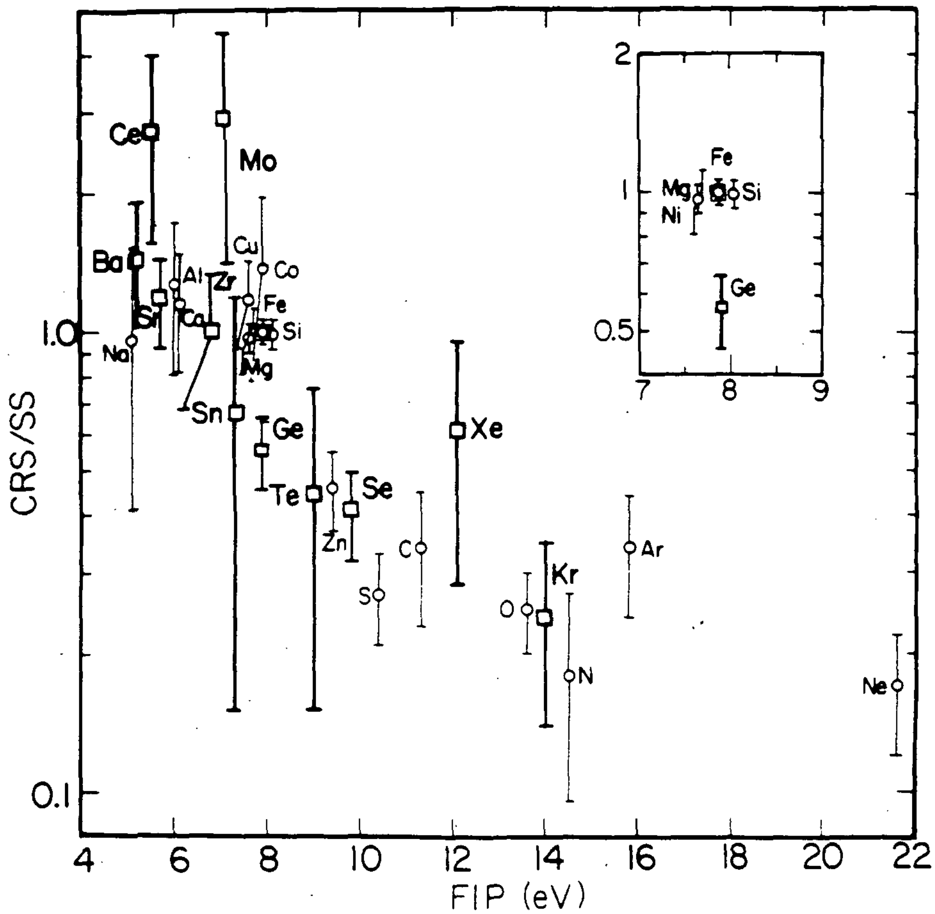

Figure 7. The ratio of cosmic-ray source (CRS) abundances to solar system (SS) abundances vs first-ionization potential (FIP). In this figure "standard solar system" abundances /5/ are used, based on C1 chondritic meteorites.

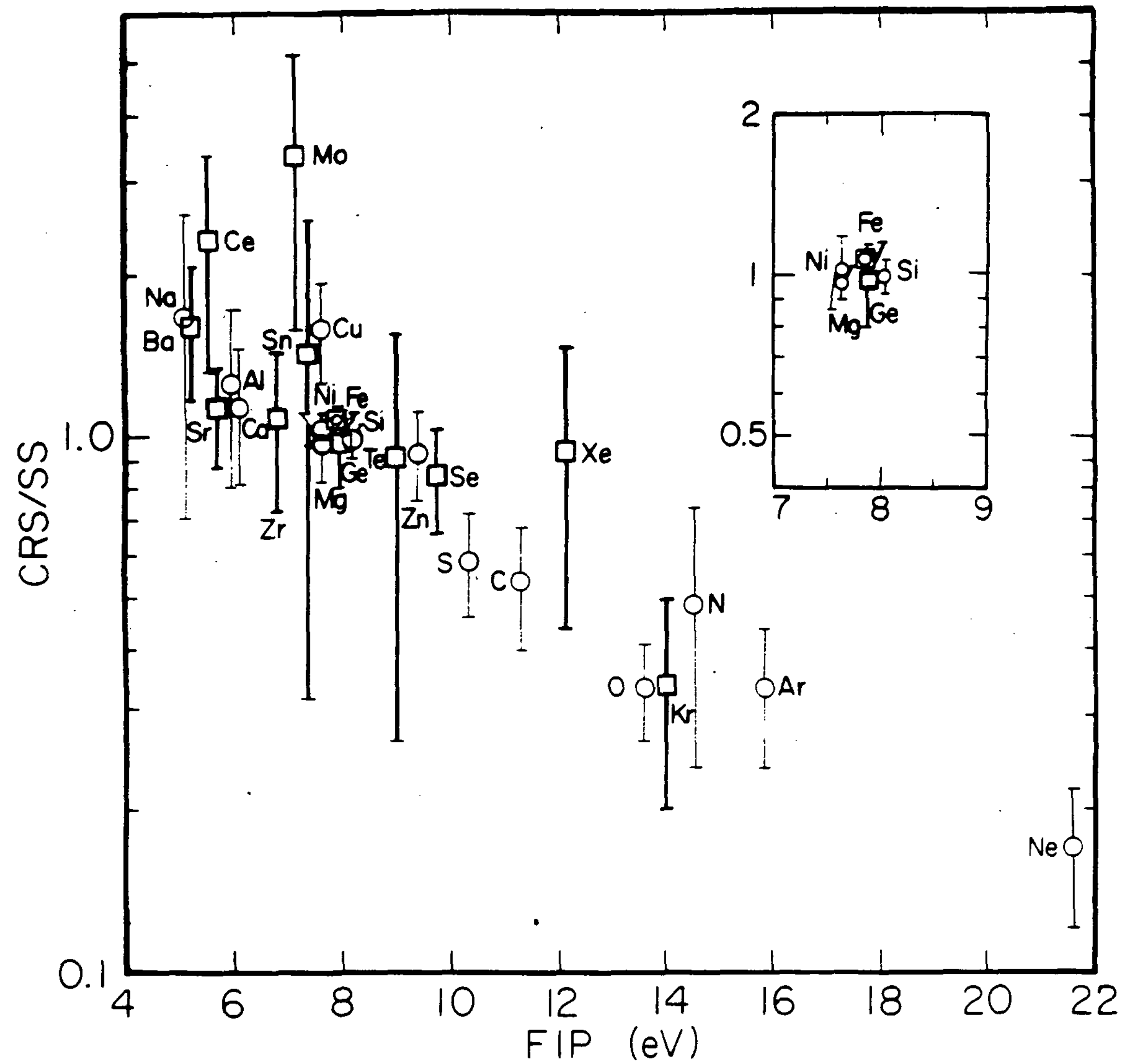

Figure 8. The ratio of cosmic-ray source (CRS) abundances to "solar system" (SS) abundances vs first-ionization potential (FIP). In this figure the CRS values are the same as those in figure 7, but the SS values are based on abundances in C2 chondritic meteorites.